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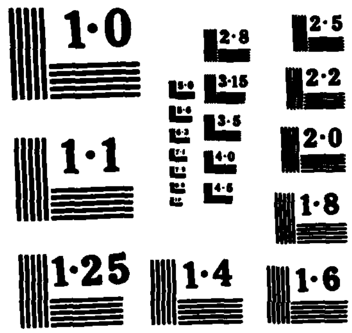

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SUBMARINE HULL INSULATION

MATERIALS SYSTEM - PHASE II

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FINAL REPORT

ON

SUBMARINE HULL INSULATION MATERIALS SYSTEM

PHASE II

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The development, fabrication, and testing of a complete submarine hull insulation materials system, based upon an anti-sweat fiberglass insulation panel is described. Recommendations for further work are outlined.

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EXECUTIVE SUMMARY

Under Contract No. N00014-84-C-2071, personnel of the Manville Service Corporation's Research and Development Center have executed a program to develop fire-resistant, anti-sweat submarine hull insulation. The Manville program has resulted in a fiberglass-based product which shows substantial promise for solving the Navy's submarine needs, and a structural concept which could also prove to be of value in solving other insulation-related problems of the Navy.

In the product submitted, one-inch-thick felts of three pounds per cubic foot density, made from five-micron diameter glass fibers are sandwiched between three-ounce, woven fiberglass scrims, sewn in place by a quilting technique which uses teflon-coated fiberglass thread. The core felts are rendered water-repellant by incorporation of a reactive silicone in the phenolic binder systems which are employed in their manufacture. The scrimmed structures are designed to be sufficiently strong in the direction perpendicular to the plane that they can be attached to a painted hull by means of a two-component, solvent-free, high-strength, spray-applied polyurethane adhesive.

The scrimmed felts are covered (on one face) with tough, woven fiberglass facings which incorporate aluminum-coated mylar films. These are employed to provide durable wear surfaces and protective water-vapor barriers. These facings are attached to the panels by use of a very light loading of a specially developed, high-strength polyurethane adhesive.

Seams are covered with fiberglass tape, and treated with a vapor-barrier coating.

Products submitted to the Navy exceeded the target property specifications in all but two of the thirty-two types of tests required. One of these shortfalls results from compromises made in design and fabrication, in the interest of achieving maximum performance with regard to those properties deemed most important, while minimizing cost. The other shortfall is due to the particular batch of facing which was used in constructing the insulation panels. The Recommendations section of the present report discusses ideas for further refinement of the product.

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INTRODUCTION

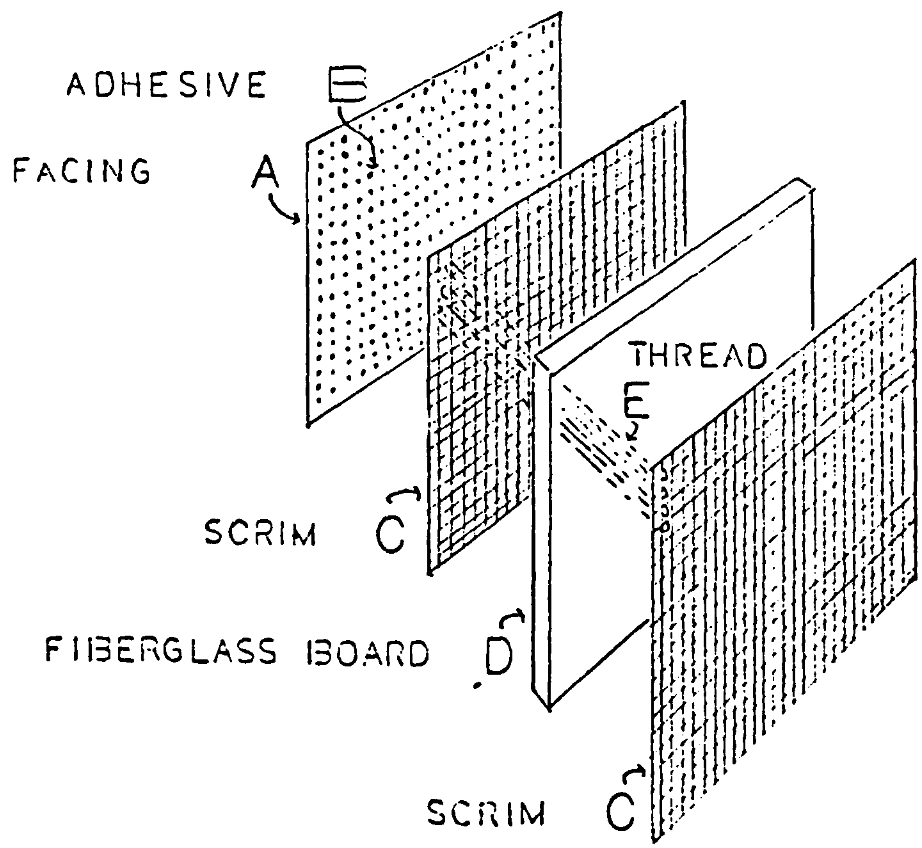
Recent experience has revealed unacceptable fire hazard associated with the present anti-sweat, submarine hull insulation (MIL-P-15280H). Generation of dense black smoke, rapid flame propagation, and production of hazardous chemical species have been observed when the insulation is exposed to a representative fire threat. Under guidance of the Naval Research Laboratory, the Manville Research and Development Center has undertaken to develop a substitute Hull Insulation Materials System to meet the Navy's requirements, under Contract N00014-84-C-2071. That contract provides for a Phase II development and manufacturing effort as a follow-on to the Phase I, initial development program carried out by Manville under Contract Number N00014-82-C-2389. The work treated in this report was carried out in the period, December 1983 to March 1985.

PROGRAM OBJECTIVE

The stated objective of our work has been to develop and to manufacture a 2000 square foot sample of a complete Hull Insulation Materials System, based upon a fiberglass felt insulation, but also including an anti-corrosion coating for the submarine hull as well as a means of attachment and a decorative coating system. This complete Hull Insulation Materials System was designed to meet the Navy's property specifications and will be amenable to full-scale manufacture in Phase III, by methods developed and tested in Phase II.

DESCRIPTION OF THE HULL INSULATION MATERIALS SYSTEM

The Hull Insulation Materials System is described, from the surface of the submarine hull, progressing inward, as follows: a corrosion-resistant coating on the sandblasted steel hull, a light loading of high-strength polyurethane adhesive, a scrim-sewn fiberglass felt insulation with vapor barrier facing, a fiberglass tape with vapor resistant coating along the joints of the panels, and finally, a decorative coating of fire-resistant paint. The figure below illustrates the structure of the Insulation System which is incorporated in the Hull Insulation Materials System.



DISCUSSION OF EVOLUTION OF COMPONENTS OF HULL INSULATION MATERIALS SYSTEM

Manville scientists and engineers enlisted the help of members of a consultative team, consisting of J. J. Henry, Naval Architects, Devoe Marine Coatings, Claremont Company, and the National Starch and Chemical Company. Each organization contributed from its considerable store of pertinent expertise, in the development of individual components and of a practical, complete system.

PRIMER

Devoe Marine Coatings, represented principally by Mr. David Bloodgood, served as our coatings consultant. At his suggestion, we considered two candidate primers, both products of Devoe. The first, a water-base paint, was very clean in fire/smoke tests, but was not outstanding in adhesion or in resistance to abrasion. We chose Devoe's Devran 201, an epoxy product, since its corrosion protection, strength, bonding to steel, and tolerance of relatively low application temperatures were superior. The disadvantage of the epoxy system is that it is carried in a xylene and methyl amyl ketone solvent for ease of spray application. Thus, complete curing with adequate ventilation at proper temperatures is essential before the paint is covered by a vapor barrier.

ATTACHMENT ADHESIVE

At the outset we chose as our adhesives consultant the National Starch and Chemical Corporation. Our initial studies, of fire-resistant, water based adhesives gave disappointing results. These products, as a group, are mechanically weak, and absorb unacceptably large quantities of water. After spending some time working with various adhesives currently used in submarine construction, we decided that none suited our purposes. In our view, an adhesive used for attachment of insulation panels in a submarine must have very special properties. Because of the necessity to cut insulation pieces to fit around obstructions, and the difficulty in reaching some portions of the hull, it is desirable to have a few minutes' working time for adjustment between first contact and attainment of maximum bond strength of the adhesive. Because we seek to attach an insulation containing an efficient vapor barrier to a steel hull, it is essential that the adhesive used for the attachment not depend upon loss of any solvent, including water, for its cure. Any molecules of solvent left between these barriers would only very slowly be lost to the outside environment, if at all. The entrapment of water brings the hazard of corrosion; the entrapment of combustible solvents brings the risk of amplification of a small shipboard fire into a disaster.

In conversations with representatives of the Foster Division of H. B. Fuller Company, we clarified some confusion about the compositions of four adhesives which that firm sells for use in marine environments.

Product Number	Type	Solvent Content	Application Method	Coverage (ft^2/gal)
82-44	contact	xylene	brush, roller	75-100
30-04	cement	water	brush, spatula	40-75
82-40	contact	methylene chloride 83% wt.	brush, spray	75-100
82-48	mastic	aromatic hydrocarbons 20% wt.; water 3%	trowel	25-50

Adhesive number 82-44 is inappropriate for use with fiberglass felt insulations having vapor-impermeable facings, as entrapment of flammable solvent is a problem. This adhesive is designed to be applied to both surfaces to be bonded, and after a period of 10 to 30 minutes, the surfaces are pressed together. In tests at our laboratory, even after periods exceeding 60 minutes, the presence of xylene was quite apparent from observations of weight and odor of the fiberglass felts. After 90 minutes, the insulation was pressed to the steel surface of the hull mock-up. After 48 hours of curing, the insulation sample was peeled from the steel, and two observations were made: the bond was very weak, and the odor of xylene was still quite strong.

For Foster 82-44, as for 3M's Fastbond 30, which we had investigated earlier, the contact cement dried satisfactorily on the steel surface, but failed to do so on the fiberglass felt. The drying of the top layer of adhesive produces a thin, rubbery skin which serves as a vapor barrier, preventing efficient removal of the remaining solvent. The solvent, therefore, permeates the body of the felt, and remains as a potential fuel source. We are particularly anxious to avoid introducing any fuel into our Hull Insulation Materials System, and are especially concerned about xylene, which generates great quantities of soot as it burns.

Adhesive 30-04 has a low tensile strength, and has been demonstrated to be a poor choice for attachment of insulations containing barriers which inhibit the loss of water, a process essential to curing.

Adhesive 82-40, because of its high methylene chloride content, presents serious ventilation problems. Further, it is not suited to application upon fiberglass felts because of its "skin formation" problem. Finally, this material does not have the 20 psi tensile strength specified by the Navy.

Adhesive 82-48 has high strength, and at first glance its relatively low (20 percent) aromatic hydrocarbon content is attractive. However, its low coverage leads to other problems.

First, the total quantity of aromatic solvent released per square foot of installed insulation is approximately equal to the total quantity of xylene per square foot for the case of 82-44. The practical considerations of fire hazard and ventilation requirements make this unattractive for extensive use in confined spaces. We have the problem of disposing of some three tons of xylene in the course of fitting a representative submarine with 120,000 square feet of insulation (see below).

Second, at a solids content of nearly 10 pounds per gallon, the weight of adhesive required to attach insulation to the inside of a submarine is significant, even if we assume the rather optimistic coverage value of 40 square feet per gallon. Let us use the figure of 120,000 square feet per submarine as an example for calculating weights of various attachment systems. On this basis, a submarine would require 15 tons of 82-48 for attachment of the insulation to the hull. (This represents, just for the attachment of the insulation to the hull, a weight of 0.25 pounds per square foot, or one third of the total specified weight of the Hull Insulation Materials System.) Should this material also be chosen for the attachment of facing to felt, the total weight of adhesive would be 30 tons, a value considerably higher that the estimated four tons required to do the fastening by means of welded metal studs.

We decided that if we were to achieve high laminar tensile strengths, and at the same time supply very little fuel to the system, and simultaneously guard against solvent entrapment, our best adhesive choices were epoxies and polyurethanes. Epoxies are more common, but most are too viscous for spray application without the addition of solvents, and in our fire tests they generated more smoke than was produced by polyurethanes.

Commercially available polyurethanes have tensile strengths in excess of 20 psi at loadings of the order of 6 grams per square foot. For our example of 120,000 square feet of insulation per submarine hull, the weight of adhesive required at such loadings would be less than a ton. Modern urethanes are free of organic solvents, are of sufficiently low viscosity to be applied by spray equipment, and can be tailored to specific situations, with curing times ranging from seconds to days. We decided polyurethanes were the most attractive solution to our attachment problems, and because of their breadth of experience with these compounds, the staff of 3M Corporation's Adhesives, Coatings, and Sealants Division seemed best equipped to advise us.

Toxicity aspects of polyurethane adhesives, which contain isocyanates, must be considered. 3M scientists assured us, however, that MDI, an isocyanate of relatively low toxicity, is the one used in their products, that it is used at low levels, and that is is not added in excess of the stoichiometric quantities required for reaction. Further, because of the adhesive's relatively high viscosity, there is never an appreciable quantity of finely divided liquid in the spray, and thus there is never a good opportunity for evaporation of isocyanates. The spray gun chiefly generates large, non-respirable droplets, and these react so rapidly that the evaporation of MDI from them is negligible. We feel that on balance, the hazard to installation personnel from the very low levels of isocyanates liberated from this polyurethane adhesive is actually lower than the hazard presented by the rather high levels of organic solvent fumes resulting from the adhesives currently in use in submarine construction. Accordingly, our choice of adhesive for attachment of insulation to hull is the special 3M polyurethane, type XA-3576, developed for this project. This adhesive was applied by spray gun, at a loading of 4 to 6 grams per square foot.

In our application of polyurethane hull adhesive to the Fire I Test Chamber, we sprayed adhesive onto the steel hull surfaces for installation of flat panels, and used the initial tack of the adhesive to hold panels in place. We experienced problems, however, because the adhesive had been formulated for use between 60^{o}F and 70^{o}F, and the steel's temperature was only 40^{o}F to 45^{o}F. We decided that because the curing reaction was progressing rather slowly, we would wait for the adhesive to develop its maximum tack before attaching the panels. This meant, however, that by the time the panels were pressed into place, the adhesive's viscosity had become too great to allow thorough wetting of the surfaces to be adhered. We wish to emphasize that this reflects not a fault in the type of adhesive employed, but rather a weakness in application method used in the test. On the basis of our laboratory experiments, it is clear that we would have obtained much better adhesion had we applied the panels sooner, when the viscosity of the adhesive was low and good wetting of the surfaces was easy. In such case, the panels could be held in place by means of simple strips of lath bowed between the framing members. Alternatively, we might have reformulated the adhesive to suit the hull temperature, or rented a large propane-fueled heater and warmed the test chamber.

SCRIM

A fiberglass scrim is sewn onto both sides of the fiberglass panel to provide a lightweight, tough surface for application of adhesive. It is important that scrims be non-burning and somewhat elastic. Our studies upon absorption of liquid water by the Phase I Hull Insulation System showed that a major location for water entrapment is the holes in the structure of the sewn-on scrim. We found that a tightly woven, lightweight fiberglass scrim left little opportunity for water absorption. Further, by effecting a good match between shapes of facing and scrim, it made strong bonding possible between these two surfaces even when very low (less than 3 grams per square foot) loadings of adhesive were used.

We were concerned with mechanical flexibility of the insulation system, and wanted to be sure that panels could bend sufficiently to wrap around the framing members used in submarine construction and to sustain other bends which might be required. We experimented with a number of relatively elastic scrim structures, including a knit fiberglass fabric. The particular knit product examined was actually too elastic to perform well in tensile tests, and its loopy structure presented problems of raveling and water absorption. While our final choice of scrim, for both hull and facing sides was a woven fiberglass fabric, we do not rule out the possibility of using an elastic scrim for areas in which there are special requirements for bending with the facing concave. The scrim selected was Burlington's 1640, a three-ounce, square-weave fabric with a 20 by 20 thread count and a special non-chloride finish (type 274, applied at a 4 percent loading) formulated to meet Manville's fire and smoke requirements. The major fault in the scrim is its propensity to tear along thread lines during delamination testing. This might be corrected by incorporating heavier yarns as "rip-stops" into the scrim structure.

FIBERGLASS INSULATION FELT

There are many tradeoffs in the design of a fiberglass felt for a particular insulation application. Compression resistance must be balanced against flexibility; recovery and chemical characteristics must be balanced against density, concentration, and type of binder. Felt density, fiber diameter, and fiber orientation all can be specified by Manville engineers and produced by Manville plants to achieve the optimum performance for the insulation job at hand. We chose for this application, felts in the density range of two to three pounds per cubic foot with fibers of approximately five microns diameter, oriented with maximum feasible vertical component of fiber lay.

We approached the water absorption problem by introducing water repellent additives to the phenolic binder which gives the felt its three-dimensional integrity. Although there are commercially available many water repellent fluorocarbons, these compounds are expensive and may represent a threat of contamination of electronic equipment inside the submarine. We therefore focused our attention upon silicones, and after some experimentation with different concentrations and formulations, chose one which was compatible with our manufacturing processes and which gave us good water absorption performance.

Silicone Additive to Fiberglass Insulation

In Phase I of the present project, we investigated a number of silicone additives to the binder coating. Silicones are well accepted by industry as water repellents. They have excellent thermal and chemical stability, are non-corrosive to metals, and are considered non-burning. Reactive silicones were found superior to non-reactive compounds in both water rejection and ease of handling. Reactivity of the binder solution required special care during manufacturing.

The reactive silicone is made up as a water emulsion in phenolic binder before it is sprayed into the fiber collection chamber. The phenolic portion is five percent by weight of the fiberglass; silicone is two percent. The silicone polymerizes when the fiberglass is oven cured, and cannot be solvent leached from the binder coating system. By contrast, non-curing silicones are leached out by solvent. Our cured fiberglass felt, with reactive silicone absorbs only 0.02 pounds of water per square foot of surface under the specified water-absorption test.

Fiber Orientation, "Zeston"

An excellent structure for simultaneously optimizing compression resistance and flexibility is a special felt which we have identified as "Zeston" - (after a Manville product which is manufactured for insulation of pipes). This Zeston structure is made by first producing a conventional fiberglass felt, then cutting it into strips, rotating each strip 90 degrees, and bonding to a flexible substrate to provide maximum vertical component of fiber lay. Substantial experimentation was done with the Zeston structure in anticipation that it might prove infeasible to satisfy compression and flexibility requirements with conventional felt structures.

In order to experiment extensively with different structures which might best suit the Navy's requirements, we produced 2500 square foot lots of three varieties of fiberglass felt: the first, a one-inch felt with density of 3 pounds per cubic foot has the feeling of a board product; the second, a one-inch felt, with density of 2 pounds per cubic foot has the properties of a roll product; and the third, a two-inch, 3 pounds per cubic foot felt designed for conversion to Zeston. We found in tests at our laboratories and in installation of samples in the quarter-scale fire test chamber at DTNRDC, that the 3 pound per cubic foot formulation with conventional fiber-lay resulted in insulation panels which had adequate flexibility and were easier to handle than those of the more novel Zeston. We feel, however, that a Zeston-type felt would be of great utility to the Navy in other applications in which a combination of superior flexibility and high compression resistance is required. Our final 2000 square foot sample of Hull Insulation Materials System was based upon one-inch, 3 pounds per cubic foot felt.

A stretchable knit fiberglass fabric was incorporated into a prototype Zeston structure. A. W. McMurray Fabrics, of Aberdeen, N. C. submitted eight knit fabrics to be sewn onto the back (non-facing), side of the submarine hull insulation. Weights of these fabrics ranged from seven to nine ounces per yard; three times the weight of Burlington 1640. Elongation values ranged from twenty percent in each direction to one-hundred percent in each direction; five to ten percent was desired. When cut, each sample of fabric did ravel, as none had an anti-fraying finish. Sample KR570/D, the knit having the lowest stretch, was sent to Manville Corporation's CHAMP Shop, Manville, New Jersey, to be sewn onto a Zeston felt thirty-six inches wide and fifty feet long. The side for the facing attachment had a six ounce J. P. Stevens 7628 fiberglass fabric with a silane finish. The silane finish exhibited no smoke or flame in small-scale laboratory fire tests. The knit fabric was successfully quilted to the back side of the Zeston and provided the finished panels with sufficient flexibility for bending concave along a five foot diameter form without distortion at the edges. These panels also accommodated bends with their facing concave about radii as small as five inches without distortion. The Zeston with knit scrim had two shortcomings. First, it was more difficult to sew than the plain non-stretch scrim; second, it raveled considerably when cut. The raveling was stopped when a 15:1 diluted finish of

National Starch 72-6800 adhesive was brushed onto the fabric. When bent, the finish releases the yarn at the bend point and the fabric stretches. Inquiries were made to Burlington and J. P. Stevens as to whether the finish could be applied to a knit fiberglass. Neither had ever attempted it, nor were they able to offer suggestions as to how such a task might be accomplished. After some discussion with Navy personnel, we concluded that with respect to compression of the insulation, the prime requirement is recovery after compression, and that some sacrifice of compression resistance could be made in the interest of flexibility. Accordingly, we decided not to submit a Phase II product with a knit fabric on a Zeston, roll product. However, we believe such a product would be of special value in selected Naval applications.

SEWING

The major considerations in sewing are inter-laminar tensile strength, absorption of water, lateral spread of water, and cost. In order to accomplish the sewing job in one pass through the machine, we chose to sew on two-inch centers along just one axis of the boards. Each two foot by three foot panel is quilted with E-18, 0.02-inch diameter fiberglass thread in a channel stitch. Four stitches per inch are required to give the twenty pound per square inch delamination tensile strength. The quilting machine which we used is located at the Manville CHAMP Shop in Manville, New Jersey. It is the same special machine which is used to sew space shuttle blanket insulation and is able to quilt continuous pieces of up to fifty feet in length and four feet in width. The Manville machine is unique in its ability to sew a one-inch thick product without the pillowing effect which is caused by over-tight threads in other machines. Other shops were investigated, but we found none that could sew a one-inch thick piece and give a flat surface after quilting.

FACING ADHESIVE

Because the facing adhesive has so very little protection from a fire, its contributions to fuel and smoke are of particular importance to the performance of the complete Hull Insulation Materials System. We initiated our studies with water-base adhesives employed for this function in Phase I products.

However, all of these products exhibited low tensile strength and high absorption of water; many performed poorly in fire tests. We had considered using Fastbond 38, a widely-used 3M self-extinguishing contact adhesive carried in a non-flammable solvent. This formulation was designed for attachment of fiberglass insulation to metal buildings, and has met rigorous fire specifications (MIL-A-3316-B, Paragraph 4.4.12.1). We saw no problem with handling its chlorinated solvents in a well-ventilated factory, but were concerned that although it passes fire tests, it might lose strength at elevated temperatures. We therefore began to examine some high-performance structural adhesives. We considered epoxies, as their high strength is attractive, but found that polyurethanes produce less smoke in fire tests. Our first experiments with two-part polyurethanes of the type which we had chosen for use between the hull and the insulation system were encouraging; we found we could achieve high laminar tensile strength for the entire Hull Insulation Materials System with such an adhesive. However, in quarter-scale tests at DTNRDC, we found that although smoke production was acceptable, fuel contribution, at the selected loading of our facing adhesive, was higher that we wished. We were pleased, therefore, that we were able to simultaneously meet all of our facing adhesive goals with a reduced loading of polyurethane. Our final choice of facing adhesive in the 2000 square foot sample of Hull Insulation Materials System submitted to the Navy for testing was the newly-developed, 3M two-part polyurethane which we used for attachment to the hull, applied by spray at a loading of 2.5 grams per square foot.

FACING

We took as our starting point the facings which were used in our Phase I samples for this project. These consisted of a woven, fiberglass cloth laminated to an aluminum-coated mylar vapor barrier. The aluminum coating tends to cover pinholes in the mylar and serves as a useful reflector of radiation. Our investigations showed that the optimum thickness for the mylar is approximately 0.0005 inches. A substantially thicker layer contributes undesirably high levels of fuel to a fire; a thinner layer is not sufficiently mechanically robust to maintain its vapor barrier performance, and shows a high incidence of pinholes.

We experimented with alternative facing structures conceived and produced by Claremont, incorporating a layer of neoprene adhesive and a lightweight fiberglass scrim to bolster the aluminum-coated mylar vapor barrier. These have the advantage of flexibility and high adhesion, but introduce chlorine atoms into the Hull Insulation Materials System. Although halogens are currently permitted in submarine components (and indeed do occur), Navy personnel have told us that future specifications may drastically reduce their permitted levels. We did not wish to achieve a mere short-term solution to the vapor barrier problem; we wished to present a design which would address the Navy's long-term needs. Therefore, we used a facing (type 3267 MAU-1) produced by Alpha, incorporating an aluminum-coated mylar vapor barrier free of added neoprene.

The surface of the tight-weave fiberglass cloth accepted paints easily and it followed the contours of bending when the panel was attached to a mock-up of a submarine's hull surface. The facings supplied by Alpha for our Phase I work met the twenty pounds per square inch delamination specification. The shipments received for Phase II showed wrinkles and delaminations, and did not meet the twenty pounds per square inch tensile strength specification. Alpha's quality control problems were so persistent that we plan to use an alternative source of facing in further work.

While evaluation of the results of the Full Scale Fire Test conducted in March, 1985 upon our Hull Insulation Materials System is still in progress, it appears that our system could be improved by substituting a more temperature-tolerant film for the mylar. We have explored the feasibility of incorporating thin films of polyimide into future facings. We also feel that we could improve upon the facing we employed by taking advantage of recent progress made by adhesives manufacturers.

DECORATIVE COATING

In collaboration with our paint consultant, Devoe Marine Coatings, we chose a water-base decorative coating (Devflex). This coating has been certified by the Navy, and meets all the target values for decorative coatings specified in the contract of the present project. In our Fire I samples, we applied one light coat of Devflex, using short-napped rollers. The coating may also be applied by spray, or in small areas, by brush. We would suggest in future, for the sake of better appearance, that two coats be applied.

SEAM TREATMENT

The work statement for the present project specified the importance of low water vapor permeability of the Hull Insulation Materials System. Covering the hull with two-by-three foot panels of insulation leaves many joint seam lines unprotected from water vapor, and a considerable portion of the hull is thus vulnerable to moisture migration. We have experimented with a number of approaches to the problem of taping seams, and conclude that for most applications, the best solution is the use of a two-inch wide fiberglass tape, attached by a fire-retardant, water-base adhesive (Foster 30-04), and painted over with a vapor barrier coating (Ocean Type 1001). This combination met the target value for water vapor permeability, had moderate mechanical strength, and performed well in the Navy's Full-Scale Fire Test. Further, it lends itself to repair of damaged insulation panels.

PANEL SIZE CONSIDERATIONS

We chose to manufacture panels in the two-by-three foot size which is standard to marine hull board. We felt that this choice would simplify the passage of material through small hatches into the compartments of the submarine. If application of larger panels seemed feasible, the insulation could be manufactured to other dimensions, up to four by eight feet, as needed. Use of large panels would minimize the number of taped seams, and thus would reduce both installation costs and the level of vapor transmission. Indeed, with the dimensional tolerances held in modern submarine construction, it could prove feasible to manufacture insulation panels to specified size and shape for particular locations.

THE MANUFACTURING PROCESS FOR SUBMARINE HULL INSULATION

The manufacturing process involved three individual steps: the production of fiberglass felts, the sewing of scrims to both sides of these felts, and the bonding of a vapor-proof facing to one side of the felts. Each individual step was performed at a different plant location.

PRODUCTION OF FIBERGLASS FELTS

A semi-rigid, water repellent felt was produced in volume by a ninety-six inch wide, full-size rotary fiberglass manufacturing unit. This machine is capable of producing thousands of square feet of felt per hour at one-inch of other specified thicknesses. The dimensional stability of the felt is established by use of a phenolic binder, which holds the individual glass fibers together in a three-dimensional array. Fibers average five microns in diameter for a good balance between thermal resistance, which requires small fibers, and compression resistance, which is enhanced by larger diameter fibers. The binder, which is sprayed onto the fibers before they are formed into a mat, consists of five percent phenolic resin, two percent reactive silicone, 0.25 percent urea, and traces of additives for control of pH. Boards are cured in an oven on a chain conveyor, set so as to assure a one-inch product thickness.

The horizontal component of the fiber lay is predominantly in the direction of conveyor motion. The on-machine, panel-cutting apparatus is oriented to give the least bending resistance in the panel's long dimension. Thus, panels are made three feet in the cross-machine direction and two feet in the machine direction in order to create the bias in bending resistance. The pieces are spot checked for size and density. The density chosen for Phase II was three pcf, as this gave the best combination of flexibility and compression resistance. The fiber diameter and binder content are checked on a regular basis in the course of manufacture.

Good binder distribution is important for achievement of satisfactory repellency of water and uniformity of mechanical properties. After the binder is cured in the ovens it appears yellow on the fibers; a product with a uniform yellow color has excellent binder distribution. Most boards exhibit some small areas of low binder content. Large areas of white fiber (having insufficient binder levels) are not acceptable since these areas may lack the targeted water-repellent character. Boards are rejected if their binder distribution does not appear satisfactory.

SEWING OF SCRIMS TO FELTS

The next step in the manufacturing process is to sew fiberglass scrims to both sides of the fiberglass felt. The scrims provide strong surfaces for adhesive attachments. Scrims employed in Phase II, Burlington 1640/I274, are held on two rollers so the individual panels can be fed between the two scrims as they start into the quilting machine. The stitch direction is across the two-foot dimension to increase ease of bending the final panel in the three foot dimension. The stitch is a two-inch spaced channel stitch, four stitches to the inch, using E-18, teflon-coated glass thread, which is the largest and strongest commercially available size. By calculation, this stitch density should be expected to give the targeted twenty pounds per square inch laminar tensile strength to the product. The thread itself has a straight breaking strength of thirty-one pounds but a knot breaking strength of only nine pounds. The fiberglass yarn loses strength at the loops where the bobbin thread and spool thread join. The stitch loop around the bobbin thread is exposed on one surface of the board in manufacture, enabling the facing adhesive to make contact, permanently locking the joint so that the threads will not pull out when cut.

The quilting operation must be interrupted when thread breakage occurs and when the bobbins need replacement. Minor snarls, which can occur, do not affect the final performance of the panels, so reasonable tolerances of stitching imperfections can be set for the manufacturing process. Panels are separated by cutting the continuous scrim which joins the individual pieces.

BONDING OF FACING TO FELTS

The third and final step in the manufacture of the panel is to secure a wear-resistant, vapor-barrier facing to one side of the sewn board. The facing is a fiberglass cloth, of the type used in covering marine board, laminated to an aluminum-coated mylar film. The preferred technique for application of facing is to spray adhesive onto the facing, and press it against the bobbin thread side of the board, thereby locking the stitches. Assembled panels are then passed through a nip roller to assure good wetting of both surfaces. Finally, boards are allowed t cure for one hour before undergoing trimming of their excess facing and scrim.

In Phase II the adhesive employed was a high strength, two-part structural adhesive, supplied by 3M, sprayed by hand at 2.5 grams per square foot. In order to make best use of the small quantity of adhesive applied, the spray was applied to the smooth facing rather than to the more absorbent scrim. Due to other demands upon machines at the time and place at which we did the facing, the recommended nip roller was not available for use in this phase of the project. Therefore, the degree of contact of the facing and scrim was not as good as it would be in an actual, full-scale manufacturing operation. In any subsequent work, nip (or contact) rollers would be used to assure uniform contact of the bonded surfaces. Adhesive application would also be made more efficient, uniform, and economical by the employment of mechanized spray equipment.

CHARACTERISTICS OF PRODUCT

MANUFACTURED AND DELIVERED

Details of physical and chemical property measurements required under the pertinent contract are presented in the Appendix to this report. Specific tests and standards are identified by paragraph number as presented in the related RFP. Properties of special interest include:

- Thermal Conductivity - 23 percent below limit.
- Areal Density - 33 percent below limit.
- Water Absorption - 30 percent below limit.
- Compression Set - 88 percent below limit.
- Dimensional Change - 99 percent below limit.
- Smoke Density - At least 87 percent below limit.
- Water Vapor Permeability - 97 percent below limit.
- Chemical Stability - 60 percent below limit.
- Outgassing - below limits for each of 32 compounds listed.
- Sound Transmission and Attenuation - Substantially exceeds requirement.

Two shortfalls are noted with regard to the stated target values. These are in laminar tensile strength of the insulation system and in compression resistance of the overall system.

The shortfall in laminar tensile strength is a characteristic of the material delivered in quantity to the Navy. The weak link is in the facing lamination (Mylar to glass fabric) of the supply received from Alpha Associates, Inc., for incorporation in our product. The poor quality of lamination was not detected in time to replace the facing supply and still maintain production schedule. Previous samples, made to the same specification, had met the 20 psi requirement. We have noted quality-control and manufacturing problems of this supplier and shall seek out other manufacturers for future supplies of this non-proprietary product. Recent developments in adhesive technology can be brought to bear to ameliorate any manufacturing problems if needed.

Despite the relatively low delamination strength of the facing composite, samples of our delivered product fared no worse in shock and vibration tests than did other samples which did meet the 20 psi requirement. We understand from conversations with Navy personnel that shock and vibration were the principal considerations in establishing that laminar tensile target.

As discussed elsewhere in this report, the shortfall in compression resistance is the result of a conscious decision made in reaching a compromise among flexibility, compression resistance, and other considerations. We have felt that, because of the effect of the inelastic facing material in spreading compressive loads, the effective resistance to compression of our product is in most situations, equivalent to that of other materials which do meet the two-to-ten psi standard. If and where higher compression resistance is required, this can be achieved with standard felts at some sacrifice in flexibility or by employing the Zeston structure described elsewhere in this report.

FULL-SCALE NAVY FIRE TEST

Samples of our complete Hull Insulation Materials System were subjected to two Navy fire tests: the Quarter-Scale Test, and the Full Scale Test (Fire I). The performance requirement for each test as stated in the contract for the present project is that there be no flash-over. Because tests in Fire I require weeks of preparation and an expenditure of the order of $100,000, the Quarter-Scale Test is used for preliminary screening. Fire I is necessary, however, since it is very difficult to extrapolate all aspects of the behavior of a large fire from the behavior of a series of small fires. Further, Fire I allows the observation of a burn in a closed system, with its peculiar combustion kinetics.

GENERAL REQUIREMENTS

Under the terms of the present contract, we were required to develop and submit to the Navy for testing, a 2000 square foot sample of our complete Hull Insulation Materials System. We were invited to supervise and aid Navy-hired contractors who were to do the actual labor of the installation. We estimated the quantities of the various components required, and had them delivered to the Naval Research Laboratory. Materials delivered are listed below:

- 2000 Square feet of Hull Insulation Board (Manville).
- 4 gallons Devran 201 epoxy-base marine primer (Devoe).
- 60 gallons XA-3596 two-component Urethane Adhesive (3M).
- 3000 linear feet of two-inch fiberglass tape (Nadisco).
- 4 gallons 1001 vapor barrier coating (Ocean Chemical).
- 20 gallons Devflex decorative marine paint (Devoe).
- 20 gallons 30-04 water-base adhesive (Foster).

PREPARATION OF FIRE I CHAMBER

Following standard Fire I test procedure, we covered the inside of the chamber (hull and frames), for a width of three bays, from the level of the lower deck, all the way around the circumference of the chamber, back to the opposite side of the lower deck. We also covered the overhead above the lower deck in this section of the chamber.

We requested of the Navy that the inside surface of the test chamber, in the region specified for our sample, be sandblasted to a semi-white condition as specified by Devoe, the manufacturers of our marine primer. Once this was done, the Navy's contractors removed sand and dust by spraying with water, and allowed the surface to dry. Drying took considerable time, as temperatures in the chamber were only slightly above 30°F, but the resultant bloom of rust did not seriously impair the quality of the coating of primer.

As suggested by the paint's manufacturer, one coat of primer was sprayed onto the interior of the hull, including the framing members, in the test region. We were concerned that at low temperatures, loss of entrapped, flammable solvents might be slow, and we did not wish to have residual xylene and methyl amyl ketone trapped between the steel hull and the mylar vapor barrier. Therefore, we allowed the paint to dry for six days before the installation of insulation was begun.

On Tuesday, February 19, actual installation of insulation panels began. A crew supplied by a decorating firm, under contract to the Navy was to perform the labor under Manville supervision. 3M technical personnel were on hand to spray the adhesive, to make final adjustments in its formulation, and to monitor potential health hazards associated with it. The contractor's crew were shown the pattern for cutting pieces to fit around framing members, and were supplied with tools, gloves, and other materials furnished by Manville. Unfortunately, none of the crew had much experience with installation of insulation, and because there was daily turnover of personnel among the crew, the quality of workmanship exhibited in the cutting of insulation panels varied quite a bit from one part of the installation to another. In no place, however, was it remarkably good. Although the chamber, in the course of several earlier burns, has suffered warping, twisting, and separation of framing members from the hull surface, we felt that even novice workers, with a modicum of desire to do a careful job, could have done much better with the Hull Insulation Materials System supplied by Manville.

Cut panels were first attached to the hull sections and afterwards the framing members were covered with "bow tie" shaped pieces. One side of each deck's hull section was sprayed at a time, then panels were set into place. The adhesive had been formulated for use at hull temperatures of 60°F to 70°F. Since actual temperatures encountered were only in the low to mid forties, we decided to wait several minutes for the adhesive to acquire its initial tack before placing panels. In this way, we hoped, there would be enough tack to hold the panels in place without auxiliary clamping. We could have altered the formulation of the adhesive to accommodate this lower-than-expected temperature, but chose not do do so, as we had only one lot of material with us in Washington, and did not wish to risk ruining it.

The framing members reached temperatures of about 50^{o}F, and were covered with the bow tie pieces which had been sprayed outside of the test chamber in order to avoid the risk of spraying adhesive onto previously installed panels. The pieces were handed into the chamber to the two men doing the installation, and until their adhesive cured, were held in place with small plywood clips. Installation went smoothly and quickly in areas in which a moderately good cutting job had been done; in areas in which the cutting was sloppy, the fit of the panels was poor.

By the end of the third working day, both the hull sections and the framing members of the upper and lower decks had been fitted with insulation. On the morning of the fourth day, panels were installed on the overhead in the lower deck. The overhead was sprayed, panels were set into the fresh adhesive, and pieces of fir one by two were used to hold the insulation in place until curing was completed. Patching work filled in the gaps caused by the poor cutting job, and all seams were taped with fiberglass tape and coated with vapor barrier coating. Finally, the entire installation was given one coat of decorative paint.

INSTRUMENTATION

The Navy's Fire I facility is equipped with a number of instruments for monitoring the progress of a burn. These include several thermocouples distributed within the chamber (none were placed at or beneath the surface of the insulation samples), several remotely-controlled stainless steel grab sampling vessels for gas analysis, pressure monitors, radiometers, and particulate monitors. The chamber is also fitted with several television cameras which view the chamber from glass portholes, and one infrared television camera, located within the chamber. There are also lines for continuous conduction of gases from within the chamber to the instrumentation building for analysis for carbon monoxide, carbon dioxide, etc. Immediately before the burn, Navy personnel placed rolled newspapers at various locations about the upper and lower decks. These newspapers are used as indicators of flashover, which is the criterion stated in the contract for passing the fire test.

BURN PROCEDURE

A large, open, rectangular, steel pan, supported on concrete blocks, was positioned on the lower deck grating of the east side of the chamber between its two center framing members. This pan was filled with approximately five gallons of heptane, and after all hatches were secured, this fuel was ignited by an electric spark.

OBSERVATIONS AND DATA

(Official, detailed data were recorded by NRL personnel; the following are casual observations made by Manville Personnel.)

After the completion of the burn, hatches at the top of the chamber were opened, and exhaust fans were employed in removal of fumes and smoke. Navy personnel in fire-protective clothing and air-supply masks entered the chamber, and after ascertaining that the heptane was exhausted and that there was no residual combustion in the insulation system, examined the damage to the sample. After a few more minutes of ventilation, other observers, without special equipment, were able to enter the chamber.

There was no evidence of flashover: the newspapers located on the upper deck appeared slightly yellowed, but those on the lower deck appeared unaltered. The maximum pressure observed during the burn was 1.46 atm, and the fire did not require quenching with nitrogen. Inside the chamber, we observed erosion and serious melt damage to the fiberglass in the immediate vicinity of the fire pan; this damage was limited to the center bay, from a few inches above the fire pan to about four feet above the upper deck. We found it interesting that along and above the insides of the framing members immediately adjacent to the fire pan, the felt, although somewhat embrittled and slightly shrunken, was still intact, as was the insulation on the webs adjacent to the destroyed areas. Fire damage to the glass components was limited to the area of the center bay.

In all but the very hottest areas of the hull above the fire pan, droplets of the sprayed-on urethane adhesive were still visible, and in fact still exhibited the characteristics of a flexible adhesive, with very little charring evident. Although there were a number of insulation panels which were virtually completely destroyed by the fire, there were none which had fallen away because of adhesive failure.

On the overhead in the lower deck area, the most noticeable damage was the loss of the mylar vapor barrier to a distance of about six feet from the fire pan, and loss of the aluminum coating in the facing to a distance of about four feet. The west side of the hull, on both upper and lower decks, suffered almost no fire damage.

There was quite a lot of soot generated in the course of the burn; so much, in fact, that after about ten minutes, gas monitoring lines from the chamber to the instrumentation trailer became clogged. We suspect that the reason for this high soot production might be that this burn proceeded to the point of complete consumption of the heptane fuel supply, and did not require quenching. Than is, this burn continued into a regime of low oxygen concentration, in which incomplete combustion generates substantial quantities of soot.

CONCLUSIONS

The subject research and development effort has provided the Navy with a viable solution to its submarine-hull-insulation problem. We have developed a novel, all fiberglass structure with aluminized Mylar vapor barrier, which offers the following features:

- Fire-safe thermal and acoustic insulation.
- Adhesive mounting which eliminates need for studs and clips and can result in considerable saving of weight and cost.
- Convenient rapid installation. Flexibility allows easy fitting around frames.
- Scrim structure which encloses fiberglass board and eliminates direct handling of insulation fibers by installers.
- Low areal density.
- Low water-vapor permeability which provides good anti-sweat characteristics.
- Water repellency.
- High structural integrity; shock and vibration resistance.
- Outstanding recovery from compression.
- Tough wear surface.
- Chemical and dimensional stability.
- Corrosion protection.
- Simple and rapid repair.
- Attractive appearance.
- Resilience to provide protection to naval personnel.

Of the many properties specified in the Statement of Work, we met target values in all but two. In many cases, we far exceeded the target values. The fire performance of our system was outstanding; there was no flashover in the large-scale test.

Properties which would require improvement in order to meet all of the target values listed in the Request For Proposal were laminar tensile strength and compression resistance.

In laminar tensile strength, failures were consistently due to weakness of the lamination of the composite facing. This can be overcome by modification of the structure of the facing itself or simply by improved quality-control in manufacturing, as discussed in the Facings section of the present report.

Compression resistance could be increased at the expense of flexibility, but as discussed in the Felt section, this probably would not improve the overall performance of the Hull Insulation Materials System. Alternatively, the Zeston structure could be employed for cases requiring simultaneous maximization of compression resistance and flexibility.

RECOMMENDATIONS

1. Since in the fire test the mylar vapor barrier was the most extensively damaged component of the Hull Insulation Materials System, we suggest replacing it with a more temperature-resistant material. We have explored the feasibility of use of duPont's Kapton film, a polyimide which is compatible with our adhesives. It appears to be an attractive substitute.

2. It would be useful to conduct a survey of other potential Naval applications of adhesive-mountable fiberglass insulations, not only of the type submitted in the present report, but also of the Zeston type, for use where both flexibility and compression resistance are important material characteristics.

3. The Navy may wish to consider a small extension to the present contract to fully verify that increased adhesion can be achieved by applying the polyurethane adhesive at the design temperature for the adhesive. As noted earlier this would be expected to provide proper wetting between the steel and the insulation system and markedly increase the bond strength as compared to that observed in the Fire I installation. Manville, with 3M as a subcontractor, could make a new installation in Fire I, using the remaining insulation Manville has already supplied to the Navy. We estimate that our costs to make such an installation would be in the order of $12,000-$15,000. This assumes that the Navy would have sandblasted and subsequently cleaned Fire I for the test installation.

4. We propose that the Navy consider the need for an insulation system which would be markedly more fire resistant than that possible with the glass fiber insulation developed under the present contract. We believe that a system utilizing the design concepts developed in this contract could be extended to an insulation product system based upon refractory fiber materials rather than glass materials or upon combinations of the two. The temperature tolerance for refractory fiber materials is in the order of 2500°F as compared to about 1000°F for glass materials.

APPENDIX

APPENDIX
TABLE OF PROPERTIES

Paragraph Number	Physical Property	Specification Number	Target Values (and Results)
3.1.1.1	Tensile Strength	MIL-P-15280H, p 4.6.11	20 psi or more Passes in plane (In plane:29 psi) (Laminar: 9 psi)
3.1.1.2	Thermal Conductivity	ASTM C 177 mean T=75^{o}F	Less than 0.30 Btu/in ft^2 hr deg F. Passes (0.23)
3.1.1.3	Friability	12 samples, each one in^3, with 24 oak blocks, each one in^3, in box 7.5x7.5x7.75 in. Tumble at 60 rpm for 10 min.	Must lose less than 5% weight Passes (3.6%)
3.1.2.1	Areal Density	(exposed area)	less than 0.75 lb/sq ft Passes (0.5 lb/ft^2)
3.1.2.2	Compression Resistance	ASTM D1056 p 18.1-18.2	2.0 to 10.0 lb/in^2 at 25% defl 60 sec (1.0 lb/in^2)
3.1.2.3	Water Absorption	4x4 in. sample held 2 in. below 70-80^{o}F water for 3 min. at 2 in. Hg below atm; held for 3 more min. at 1 atm; drain 10 min., blot.	Weight gain must be less than 0.1 lb/ft^2 Passes (0.07 lb/ft^2)
3.1.2.4	Compression Set	ASTM D 1667	Must be less than 25 %. Passes (3%)
3.1.2.5	Dimensional Change	MIL P-15280H p. 4.6.8	Must be less than 10% of original length. Passes (0.1%)

Paragraph Number	Physical Property	Specification Number	Target Values (and Results)
3.1.2.6	Fire Resistance	NAVY 1/4 Scale	640 Btu/min, 10 min with no flash-over. Passes
		NAVY 200 cu ft	1000 Btu/min, 10 min with no flash-over. (No results reported to Manville.)
		NAVY 10,000 cu ft	3,000,000 Btu/hr, 10 min with no flash-over. Passes
3.1.2.7	Smoke Density	ASTM E662 (flaming and non-flaming modes)	Optical density must be less than 200. Passes (20 to 26)
3.1.2.8	Oil Resistance	MIL-P-15280H, at T - 158°F	No swelling or softening with facing breached. Passes
3.1.2.9	Water Vapor Permeability	MIL-P-15280H p. 4.6.15	Less than 0.3 perm inch with facing intact. Passes (0.01) Complete Specimen (0.09) taped seam
3.1.2.10	Hg, asbestos, CrO_4		Must be free of these. Passes
3.1.2.11	Chemical Stability	1 sq ft sample, cycle 6 times from 70° to 175°F; condition at 70°F, 50% RH.	Weight change must be less than 1% Passes (0.04%)
3.1.2.12	Flexibility		Must conform to 5 ft diameter. Passes.
3.1.2.13	Lateral Spread of Water	1 sq ft of sample, 1 inch diam hole to bottom, dam, flood with 1 inch water for 1 hour.	Spread must be less than 3 inch radius Passes

Paragraph Number	Physical Property	Specifications Number	Target Values (and Results)
3.1.2.14	Shock	MIL-S-901C	Grade B, Hull Mounting, Class II Passes (Tested by Woodward Governor, Ft. Collins, CO.)
3.1.2.15	Vibration Resistance	MIL-STD-167-1 (SHIPS)	Must withstand environmental vibration. Passes (Tested by Engineering Dynamics Englewood, CO.)
3.1.2.16	Outgassing		Seal 10 g sample in 560 ml bulb, hold at 145 deg F for 24 hr, cool, analyze headspace gases.

Compound	Target Value	Measured Value
acetone	330 ppm	less than 1 ppm
ammonia	25 ppm	less than 1 ppm
benzene	1 ppm	less than 1 ppm
chlorine	0.1 ppm	less than 0.05 ppm
CO_2	0.8%	500 ppm
CO	15 ppm	less than 0.05 ppm
total aromatic (less benzene	10mg/cu m	less than 1mg/cu m
total aliphatic (less methane)	60mg/cu m	less than 1mg/cu m
hydrogen	1%	less than 10 ppm
HCl	1 ppm	less than 0.5 ppm
methane	13,000 ppm	less than 1 ppm
methyl chloroform	2.5 ppm	less than 1 ppm
monoethanolamine	0.5 ppm	less than 0.1 ppm
NO_2	0.5 ppm	less than 0.1 ppm
O_2	140-160 torr (less than 21% vol.)	150 torr
O_3	0.02 ppm	less than 0.005 ppm
$CFCl_3$	5 ppm	less than 1 ppm
CCl_2F_2	200 ppm	less than 1 ppm
$C_2Cl_2F_4$	200 ppm	less than 1 ppm
SO_2	1 ppm	less than 0.1 ppm

Compound	Target Value	Measured Value
toluene	50 ppm	less than 1 ppm
vinylidene chloride	2 ppm	less than 1 ppm
acetylene	6000 ppm	less than 1 ppm
acrolein	0.1 ppm	less than 0.05 ppm
arsine	0.01 ppm	less than 0.0005 ppm
ethanol	100 ppm	less than 1 ppm
ethylene	6000 ppm	less than 1 ppm
formaldehyde	0.5 ppm	less than 0.1 ppm
HF	0.1 ppm	less than 0.05 ppm
isopropanol	50 ppm	less than 1 ppm
methanol	10 ppm	less than 1 ppm
stibine	0.01 ppm	less than 0.0005 ppm

Paragraph Number	Physical Property	Specification Number	Target Values (and Results)
3.1.2.17	Sound Attenuation	ASTM C423 Reverb, Room	Reduction Coefficeint must be more than 0.25 Passes (0.40)
3.1.2.18	Sound Transmission	ASTM E-90	Sound Transmission Class must be more than 31.0 Passes (35) (Tested by Riverbank Acoustics, Geneva , IL.)
3.1.3.1	Hg,Pb, asbestos, CrO_4		Must be free of these. Passes
3.1.3.2	Corrosion Protection	ASTM B-117 ASTM D-1654	Passes
3.1.3.3	Adhesion	ASTM D-3359	Passes
3.1.4.1	Fire Resistance	DOD-C-24596 p 4.6.10 & 9.6.10	Non-burning, self-extinguishing, or intumescent. Passes (non-burning)
3.1.4.2	Adhesion	ASTM D-3359, B	Passes
3.1.4.3	Surface Characteristics	Navy formula 124 ASTM D-2486 (latex) Fed Std 141, method 6143 (oil)	Manufacturer (Devoe) certifies product that the product Passes.

Paragraph Number	Physical Property	Specification Number	Target Values (and Results)
3.1.4.4	Color	Fed Std 595	Chip #27780 Conforms
3.1.4.5	Chlorinated Solvents		Must be free of these. Passes
3.1.4.6	Hg, Pb, asbestos, CrO_4		Must be free of these. Passes
3.1.5.1	Tensile Strength	MIL-A-24179 p 4.5.5 (SHIPS)	Must be greater than the strength of the insulation system itself. Note: Navy has clarified this. The target value is 20 psi. Passes

Data upon which this report is based, are recorded in Manville Corporation Contracts Laboratory Notebook No. 41.